# PROBLEMS IN CASTING PRODUCTION TECHNOLOGY
(Selected Articles)

By

Various Authors

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# CASTING OF LARGE-SIZE THIN-WALLED PARTS BY THE DIRECTIONAL STAGE CRYSTALLIZATION METHOD

V. D. Khramov and Ye. V. Mishakov

At the present time a number of branches of machine construction produces large-size cast parts of magnesium alloys up to 3 m long and with a wall thickness of 3-4 mm.

The combination of a considerable size with small wall thickness brings about a number of flaws during pouring into the molds. The basic flaws are as follows:

1. Incomplete pouring;

2. Non-metallic inclusions forming as a result of turbulent flow of the metal;

3. Shrinkage cavities resulting from interrupting the crystallization sequence.

As is known, these defects occur during casting of parts of any shape, yet they are especially strongly developed in the case of thin-walled parts having a considerable height.

Below we analyze various methods of feeding metal into the molds and show how the development of flaws changes depending on

one or the other method for the production of thin-walled large-size parts.

Basically, two methods of introducing metal into molds are utilized:

a) The usual gate-vent system with well-developed gating channels (down gate, metal receptacle, collector, gates, etc.);

b) Direct introduction of the metal into the molds (vacuum-suction casting, low-pressure casting, centrifugal casting, casting by extrusion).

## Casting Methods Based on Pouring Metals into Molds According to the Gate-Vent System

In this case metal can be poured according to the top, lower or vertical-slit gating system.

### Pouring Metals into Molds According to the Top Gating System (Fig.1)

In this case, from the pouring basin the metal is poured into the mold from the top, hence during the entire pouring and subsequent crystallization the upper part of the casting has a higher temperature than the bottom part. Thus there are created reliable conditions for successive directional crystallization which

prevent the formation of shrinkage cavities in the casting body. This is a considerable advantage afforded by the above gating system.

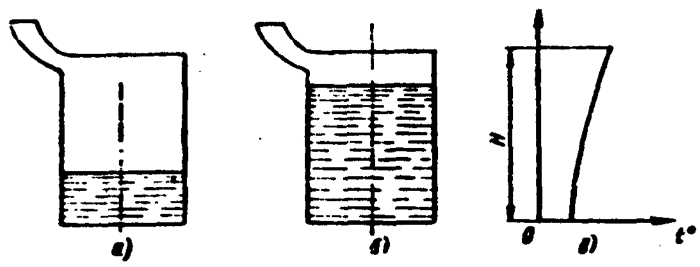


Fig. 1. Pouring metal into molds according to the top gating system. a) beginning of casting b) mean time of casting c) temperature distribution over the casting height.

On the other hand, the liquid metal poured from above splashes, catches air, forms air pockets, and oxidizes intensively. As a result, castings contain non-metallic inclusions, and in the case of magnesium alloy they may even burn up.

Such a pouring of metal into molds is possible only in the

case of aluminum alloy poured into molds whose height does not exceed 150 mm. For magnesium alloys this method is inapplicable.

For the case of casting large-size parts with magnesium alloys interesting us the above method has obviously to be completely excluded.

Pouring Metal into Molds According to the Lower Gating System (Fig. 2)

This method ensures a relatively even filling of molds and, hence, eliminates the possibility of non-metallic inclusions in castings. This affords a considerable advantage over the method described earlier. On the other hand, this pouring method has substantial drawbacks.

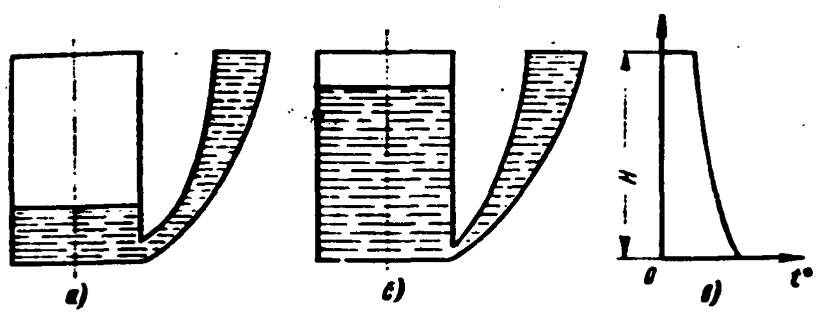


Fig. 2. Metal poured into molds according to the lower gating

systeM; a) beginning of pouring b) mean time of pouring c) temperature distribution over the height of the casting.

a) At the beginning, owing to a considerable hydrostatic head, the pouring rate of the metal is fairly high, and if the gate is close to the opposite mold wall the metal hits this wall, there occurs a fountain effect, air is caught and the metal oxidizes. If the opposite mold wall is far from the metal gate then, owing to the high initial rate, there occurs " outrunning", i.e., that ~~mf~~ part of the metal advancing at a higher velocity penetrates deep into the mold, oxidizes from the surface and finds itself disconnected with the main metal flow which reaches it after a certain time. As a result of such a phenomenon cold shuts form in castings[(1)].

b) The necessary thermal conditions are disrupted since the hottest metal is in the bottom part of the casting while its temperature in the upper part is lower (see Fig. 2c), as a result of which shrinkage cavities form in the castings. In order to avoid

(1) T.I. Orlova, "Investigating the flow rate of metals in mold channels", transactions of the First Conference on the Theory of Casting Processes, Academy of Sciences of the USSR, 1958.

this, it is possible, for example, to thicken gradually the parts from the bottom to the top removing subsequently these technological allowances by means of mechanical processing. Yet, this is not expedient since the metal flow increases abruptly, and crystallization is slowed down especially in the top portions of castings. This leads to grain coarsening and a corresponding deterioration of the mechanical properties of alloys. During pouring, magnesium alloys may catch fire owing to a considerably increased thickness of the casting walls.

The above circumstances prevent the utilization of the lower pouring method for casting thin-walled large-size machine parts with magnesium alloys.

A certain improvement is achieved by the use of ~~the~~ bottom pouring of metal followed by ~~an~~ additional pouring of hot metal into the vent. Yet, this method is also not applicable for casting thin-walled parts of considerable height since it brings about defects characteristic of both the top and bottom metal pouring.

The advantages of top and bottom pouring are best combined in the case of a gating system called the vertical slit system.

<u>Pouring Metal into Molds According to the Vertical-Slit Gating</u>

System (Fig. 3)

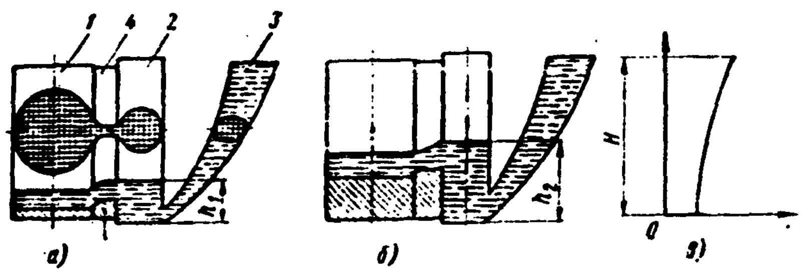


Fig. 3. Pouring metal into molds according to the vertical-slit gating system. a) beginning of casting b) mean time of pouring c) temperature distribution along the height of castings. 1. casting 2. pit 3. sprue 4. vertical slit.

The portion of the gating system between the pouring basin and the inlet channels into the pits represents a conventional lower gating system 3.

The metal enters pit 2 whose relatively great diameter prevents the alloy flowing through it from solidifing during the

entire time required for filling the mold. From the pit the metal flows through a vertical slit 4 into a hollow forming part 1. The size of the slit is such that the metal flowing through it solidifies without holding as the metal level rises in the mold. Since the level of the metal flowing through the slit rises gradually each elementary metal layer lying higher in the hollow of the mold of the part has a higher temperature during cooling than the layers lying below, i.e., there formed a temperature field characteristic of metal pouring from the top. Thus, the necessary thermal conditions are created and successive crystallization is ensured.

Under actual service conditions it is extremely difficult to regulate the solidification of the alloy in the vertical slit without holding as the metal level rises in the mold in such a way as to obtain a correct operation of the vertical slit system. Most frequently it operates either as the top or the bottom gating system.

Such disorders in the operation of the vertical-slit gating system are observed all the more frequently, the larger the size of the part being cast. When casting parts with dimensions mentioned

above, these disorders and, hence, the defects caused by them, can practically not be eliminated. For this reason the above method is also found to be impracticable for the solution of the assigned problem.

## Casting Methods Based on Introducing the Liquid Metal Directly into Molds

### Vacuum Suction Method

In this case the ~~liquid~~ liquid metal is sucked into the mold owing to the formation of a vacuum in it. (Fig. 4)[1].

Theoretically, this method can be adopted for casting thin-walled parts of considerable height from magnesium alloys. Maximum suction height H, i.e., maximum height of obtainable castings, is determined by the formula

$$H = \frac{760 \cdot 13{,}6}{\gamma_{ж}} \approx 6000\ мм, \qquad \text{A 9}$$

where 760 is the height of mercury in the tube in the absence of counterpressure, in mm;

(1) P. M. Ksenofontov, Lit'ye metodom vakuumnogo vsasyvaniya (Casting according to the method of vacuum suction), Mashgiz, 1952.

13.6 is the specific weight of mercury, in g/cm$^3$;

$\gamma_{liq}$ is the specific weight of liquid magnesium alloy, in g/cm$^3$

As a matter of fact, owing to intensive heat removal through the lateral walls it is difficult to raise the metal to a considerable height, and hollows form in the case of small wall thickness, hence the real maximum height of castings obtainable by this method is considerably less. High filling rates excludex hollows but bring about turbulent flows which , in turn, provoke non-metallic inclusions. When utilizing the above method there is no danger of shrinkage cavities since the crystallization process takes place successively from the top to the bottom. Despite the advantages mentioned above, this method is equally inapplicable for casting with magnesium alloys large-size parts whose height attains 3 m.

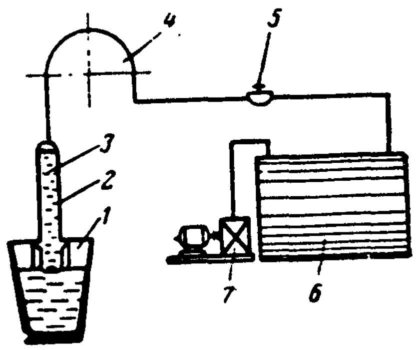


Fig. 4. Principal scheme of vacuum-suction casting. 1. crucible 2. mold 3. liquid alloy 4. rubber hoses 5. vacuum depth regulator 6. vacuum cylinder 7. vacuum pump.

## Low-Pressure Casting

Low-pressure casting differs from other methods in that the liquid alloy in a hermetically sealed crucible is fed into the mold through a steel duct under pressure exerted on the alloy surface by an inert gas (argon) or compressed air. Pressure in the crucible increases proportionally with the resistances encountered by the alloy in the hollow of the mold.

Inherent in this method are the same drawbacks characteristic of the vacuum-suction method, hence it is also inapplicable for the production of large-size parts.

Thus, utilization of the casting methods described above does not afford the possibility of obtaining castings having considerable heights and small wall thickness.

Such parts can be cast according to a new method called the method of directed successive crystallization which combines successfully the advantages of upper and lower metal pouring without having their disadvantages.

The Method of Directed Successive Crystallization

Essentially, the method consists in that during casting the liquid metal pours into the mold through sprue tubes. The mold is lowered while the sprue tubes are stationary, owing to which the liquid metal fills continuously overlying portions of the mold.

The mold begins to travel downwards at the moment where the bottom of the sprue tube plunges 50-100 mm into the metal, and during the entire period of casting this position is maintained unaltered, i.e., it is as though there were a closed transfusion of metal.

From the pouring basin the liquid metal passes through the sprue tubes into the mold receptacle, and then, as the level rises, it flows through the slit gates directly into the hollow of the mold.

The motion of the metal in channels of constant height formed by tubes can be compared with the motion of the metal in a sprue of a lower gating system where a cascade extrusion of the metal cannot take place.

Another great merit of this method consists in the possibility of regulating the feed of the melt into the mold. This fact enables us to fight turbulent flows at the sprue outlet. Plunging the bottom ends of the pipes below the metal level in the mold is an additional means ~~of~~ for filling molds fairly steadily and obtaining castings with negligible amounts of non-metallic inclusions. However, the melt pours into the mold almost at the level of the cast metal surface and as this level rises the liquid metal inlet continuously changes its place as well. It follows that, like in the case of the upper gating system, a temperature increase of the casting metal is ensured in an upward direction and, hence, a successive crystallization takes place in the same direction.

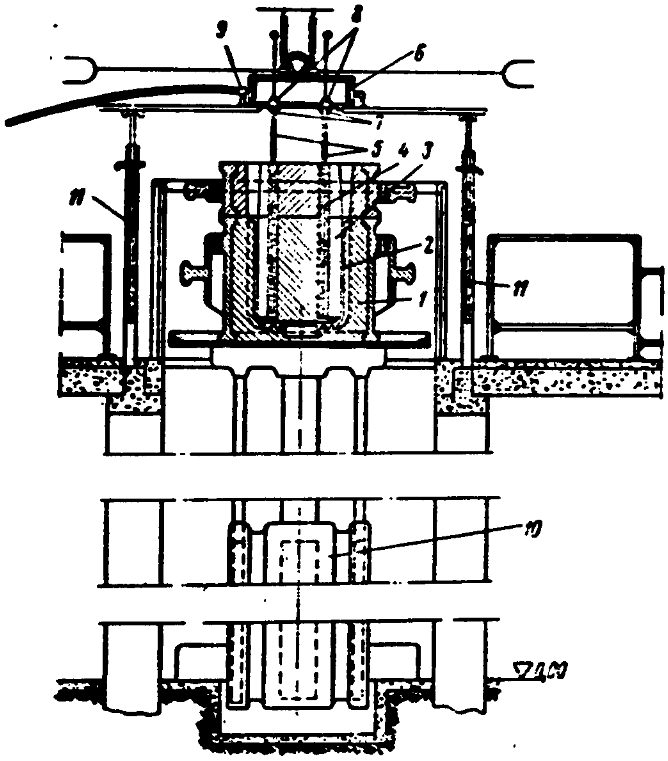

Fig. 5. Basic diagram of an installation for casting according to the directed successive crystallization method. 1. mold 2. casting 3. slit gates 4. vertical pits 5. sprue pipe 6. pouring basin 7. openings in the pouring basin 8. stopper 9. gas burner 10. pull-broaching device 11. pouring basin supports.

The directed successive crystalization of casting is the basic merit of the above method. It eliminates the formation of shrinkage cavities and requires almost no vents. Finally, continuous feed of liquid metal to the surface line eliminates the formation of cavities and makes it possible to produce castings of unlimited height.

Below we give a more circumstantial description of the directed successive crystallization method.

A mold (which may be made either of sand or metal) (Fig. 5) contains vertical pits 4 traversed over the entire height of the part by gate slits 3 with a thickness of 4-7 mm.

The assembled mold 1 is placed on the platform of the pull-broaching device 10 which has a hydraulic or mechanical drive.

Above the mold, on special supports 11, a pouring basin 6 (made of welded steel sheets or cast) is placed in such a way that its holes coincide exactly with the mold pits.

The holes of pouring basin 7 are sphere-shaped and closed by sphere-shaped stoppers 8. The bottom end of the sprue tube reaches to a distance of 30-50 mm from the bottom of the pits.

A gas burner 9 is set up around the pouring basin. This burner heats the basin continuously prior to casting and during it. The sprue tubes are also heated either in a special furnace or directly in the mold (electric heating). Casting is effected from the crucibles by means of a bridge crane

When the pouring basin is filled with metal the ball stoppers are removed and the metal pours through the sprue tubes into the pits and from there through the slit gates into the mold.

At the moment when the system is filled and the bottom end of the sprue tube plunges into the metal for 50-100 mm, the mechanism lowering the pull-broaching device is switched on.

The rate at which the molds are lowered must be minimal. In the ideal case it equals the linear crystallization rate of the casting along its height.

Pouring of Liquid Metal

Liquid metal can be poured into the molds by different methods.

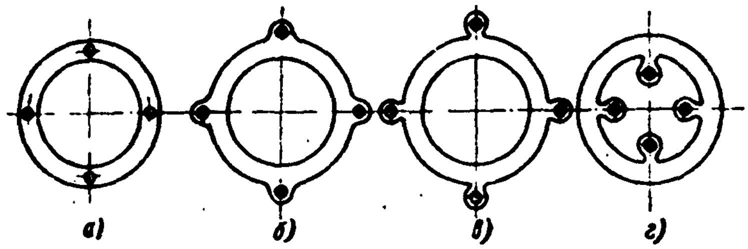

Fig. 6. Standard methods of pouring liquid metal into molds.

Figure 6a shows a method of pouring metal directly into the body of the casting by means of four tubes. This is possible when the casting wall is sufficiently thick to contain pipes. Fig. 6b shows how to pour metal through tubes into special ribs which are subsequently removed. This method is more successful and should be used where the design permits it. The ribs are some kind of an addition and add metal to the most heated parts of the casting at feed points.

Figure 6 c illustrates how metal is fed through special pits and vertical slits from the outside, while Fig. 6 d shows the same from the inside. The latter method reduces considerably the dimensions of molds but is inapplicable if the shape of the inner casting surface is complex.

Metal Receptacles with Drains

Metal receptacles or drains 2 serve to isolate the first portions of liquid alloys. The volume of each receptacle should be equal to one or two volumes of liquid metal contained in the tube. There may be individual receptacles for each sprue tube 1 or common receptacles for all tubes; the latter version is preferable.

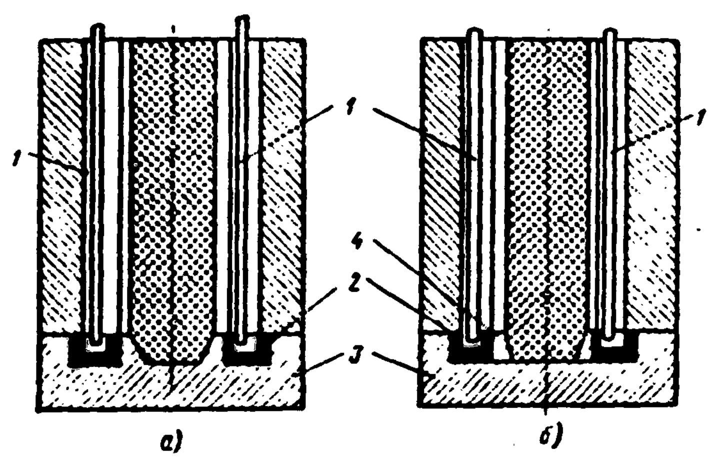


Fig. 7. Casting mold with metal receptacles.

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Fig. 7. Casting mold with metal receptacles.

Metal receptacles in the lower metallic slab of the mold should be so designed as to prevent interference with free casting shrinkage and the formation of tracks.

Figure 7a shows the incorrect design of a metal receptacle since it is rigidly joined with the stool 3 thus interferring with shrinkage during the crystallization process.

Figure 7b shows the correct design. Here, a damper 4 is provided in the form of a sand or earthen shutter which is easily removable during crystallization and shrinkage of the casting and

does not bring about additional stresses or cracks in the casting.

In the case where the metal receptacles touch only the inner drawback of the mold without penetrating into the stool no special dampers are required.

<u>Passage of Liquid Metal Through Sprue Tubes During Casting</u>

In order to prevent premature solidification of the metal while it flows through the sprue tubes, special measures have to be taken, such as heating the tubes up to 700-800°.

<u>Preliminary heat-up of tubes</u>. Sprue tubes are gas-heated outside the molds and placed into them immediately prior to casting.

As already noted, the main point of this method consists in the fact that the rate at which the mold mounted on the table of the pull-broaching device is lowered must approach the linear crystallization rate of the casting along its height.

In order to fulfill this condition the quantity of metal flowing through the sprue tubes must be small, i.e., the diameter of these tubes must be small (12-16 mm).

Since for tubes with such a diameter the relative lateral surface is great, the metal flowing through them cools rapidly. For example, at a casting temperature of alloy ML5 of 760-780°

and the diameter of the tube heated beforehand in a gas stove equalling 12 mm the metal solidifies if the sprue is 500-600 mm long; with a diameter of 14 mm it solidifies with a length of 800-900 mm, and with a diameter of 16 mm it solidifies if the sprue has a length of 1500 mm.

This takes place because during the time interval between the withdrawal of the spure tubes from the gas stove and the instant of casting (3-5 min) they cool off rapidly owing to the small thickness of the wall (1.0-1.5 mm), and preliminary heating is little effective.

Thus, preliminary heat-up of tubes is expedient only when casting low molds, whereas utilization of tubes with small cross sections for casting parts 2000-3000 mm high must be excluded altogether.

<u>Utilization of sprue tubes with nipples.</u> In this case, as a sprue we utilized steel tubes with a diameter of 18, 20 and 22 mm and more. The higher the part, the greater the required cross section of the sprue.

In order to regulate the metal flow, a nipple with a hole is inserted up to 10-15 mm in the bottom tip of the tube. It is the

diameter of the nipple hole to determine the liquid metal flow during a time unit when pouring from the sprue.

In this case the metal in the sprue does not solidify since above the nipple there is a large volume of liquid metal and the relative lateral cooling surface is considerably reduced.

Graphite nipples, tightly inserted in the tubes after the first casting, is "welded" to the surface and adheres quite reliably. Prior to each casting its hole is checked by an appropriate gauge and in the case of deviations from the assigned dimensions the nipple is replaced by a new one.

Utilization of sprue tubes heated electrically. Figure 8 shows two systems of electric heating of sprues which are actually utilized in production today.

According to version I, from a reducing transformer with a power of 75 kw, a voltage of 24-30 v and a current intensity of 200-400 a the current is fed to the bottom tips of the tubes by means of steel conductors with individual terminals, and to the top ends of the tubes - through the body of the basin.

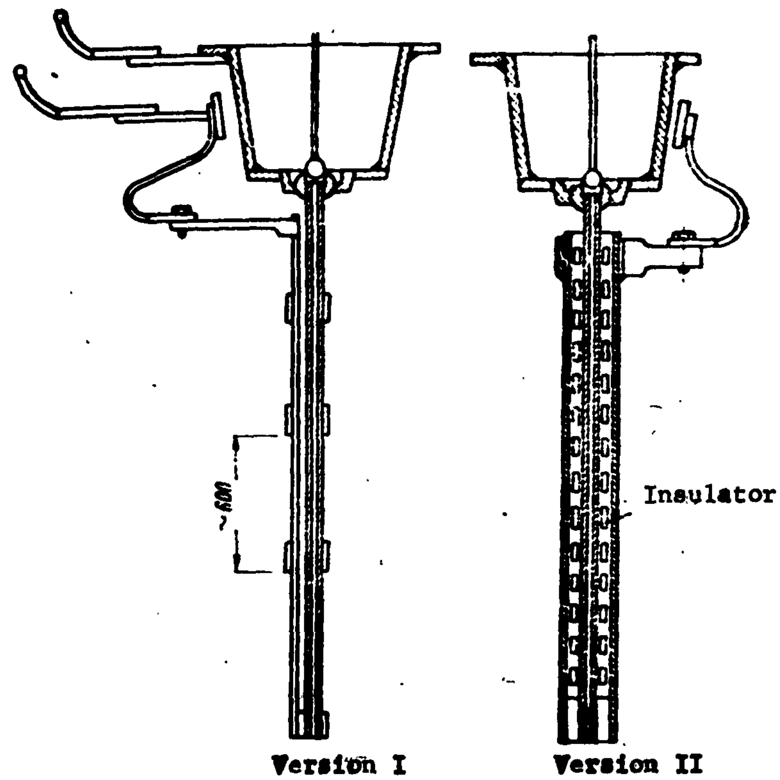


Fig. 8. Diagram of electric heat-up of sprue tubes i

The mobile steel rod is held by sliding insulators, hence it does not join with the sprue tube. This allows the tube to expand during heating. The device is clearly seen in the figure.

According to version II (Fig. 8) the feeding conductor is the outer tube. Insulation is provided between it and the sprue tube.

For the rest, the heating principle is the same as in version I.

Such electric heating systems were tested on sprues with an inner diameter of 12 mm and a height of 3500 mm. They proved to be worth while for operation. The sprue tubes are heated for 1-2 min up to 750-800°. This ensures constant temperature of the liquid alloy during its flow through the sprue and eliminates the possibility of a premature solidification.

The sprue tubes can be made of steels of any brand.

When using electric heating, steels with high ohmic resistances are desirable.

## Some Theoretical Premises for the Planning of Technological Casting Processes According to the New Method and Practical Interferences

In order to plan correctly the technological casting process according to the directed successive crystallization method we must solve problems connected with thermo-physical and hydrodyhamic phenomena occurring during the casting of liquid metals into molds.

When planning the casting process under investigation, in

particular in the case of magnesium alloys, one should proceed not from the thermal processes but from hydrodynamic calculations connected with the rate # of flow of liquid metal at the outflow from the sprue tubes and the rate at which the metal rises in the mold. Thermal calculations must be carried out for checking.

Serviceable castings with no slag inclusions can be obtained only under specific conditions of filling the molds.

When pouring alloys into molds with the aid of sprue tubes we have a hydraulic scheme of the outflow of the liquid from the large container (pouring basin) through a small hole in the bottom.

This corresponds to the formula for metal flow

$$q = \mu\omega\gamma\sqrt{2gh}, \qquad \text{A 16}$$

where q is the fluid rate of flow in g/sec;

$\mu$ is the flow rate factor;

$\omega$ is the cross-sectional area of the tube aperture, in $cm^2$;

$\gamma$ is the specific weight of liquid alloy, in $g/cm^3$;

g is gravity acceleration equalling 180 $cm/sec^2$;

h is the tube height, in cm.

Numerous tests were conducted in order to determine the flow rate coefficient and the specific rate of flow q in the

case of electrically heated sprue tubes.

It was established that the flow rate factor increases as the cross section of the tube increases, and drops as the sprue height grows (all other conditions being equal). Thex specific rate of flow changes in a similar fashion.

The tests were donducted with a special model with water and liquid alloy ML5.

Figures 9 and 10 show the characteristics mentioned above for the most generally used sprue tubes in accordance with their height and cross section, while Table 1 gives the specific rate of flow of liquid alloy ML5 during the casting of various parts.

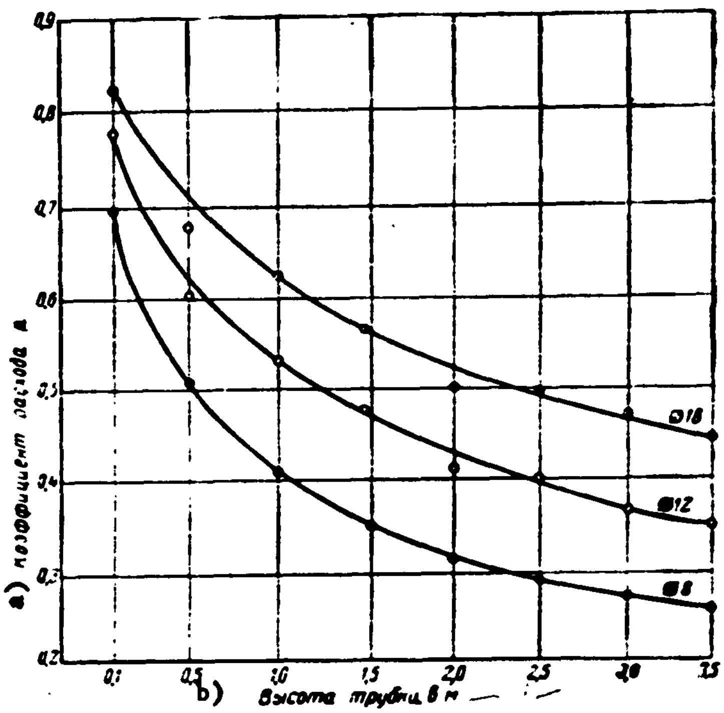


Fig. 9. Depen-ence of flow rate factor $\mu$ on the diameter and ..eight of sprue tubes for alloy ML5. a) flow rate factor $\mu$; b) tube height, in m.

Table 1

Specific rate of flow q (in g/sec) of liquid alloy ML5 during outflow from electrically heated sprue tubes, according to service data.

| a) Высота трубки-стояка мм | b) Удельный расход в г/сек при диаметре трубок-стояков в мм | | | |
|---|---|---|---|---|
| | 12 | 14 | 16 | 18 |
| 1000 | 352 | 479 | 535 | — |
| 1500 | — | 728 | 1025 | 1392 |
| 2500 | — | 710 | 1068 | 1535 |
| 3500 | — | 683 | 1191 | 1524 |

a) height of sprue tube, mm, b) specific rate of flow in g/sec, diameter of sprue tubes in mm.

It was noted earlier that calculations of the technological casting process should be based on hydrodynamic characteristics since the quality of the casting ~~[illegible]~~ depends in the first place on their correct choice, especially in the case of aluminum and magnesium alloys.

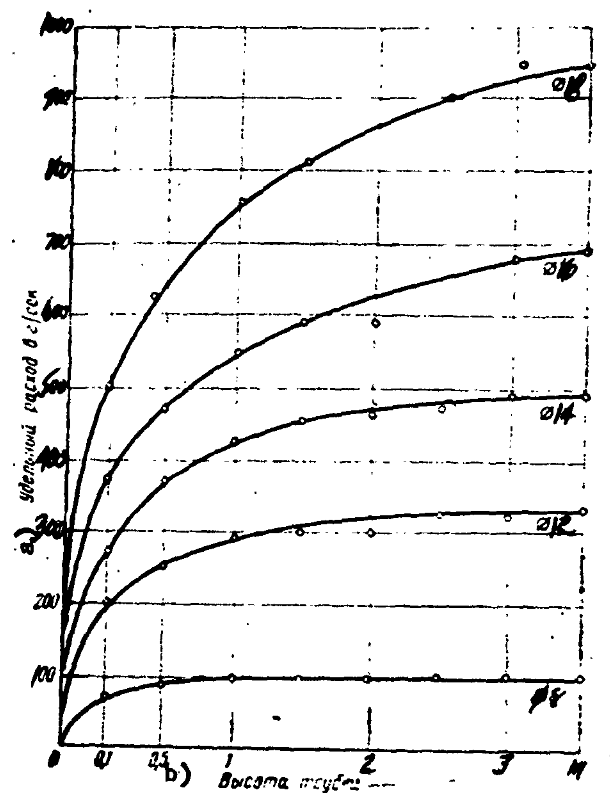


Fig. 10. Dependence of specific rate of flow on the diameter and height of sprue tubes for alloy ML5. a) specific rate of flow in g/sec b) tube height.

Numerous tests conducted with samples and working parts established that slagging of castings depends only on the rate at which the metal rises in the mold, excepting those cases where initial slags from the metal get into the castings. [redacted] formation of secondary slags on aluminum and magnesium alloys results from the

oxidation of the metal while filling molds during its turbulent flow in the mold where there exists a possibility of interaction with the oxygen from the air.

Thus, formation of secondary slag inclusions can be avoided only under such conditions in the mold where turbulent flow cannot occur.

It ensues that there exist some critical velocities of the rising of the metal in molds which, when exceeded, bring about turbulent flow and create favorable conditions for enhanced oxidation of the alloy and formation of secondary slags in the form of magnesium oxide inclusions for magnesium alloys, and aluminum oxide inclusions for aluminum alloys.

This critical velocity is determined by the Reynolds number:

$$Re > \frac{4Rv}{\nu}, \tag{1}$$

where v is the critical velocity at which the metal rises in the mold, in cm/sec;

R is the hydraulic radius, in cm;

$\nu$ is the kinematic viscosity factor in $cm^2/sec$

$$\nu = \frac{\mu}{\rho},$$

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where $\mu$ is the dynamic viscosity factor in g sec/cm$^2$;

$\rho$ is the density in g/cm$^3$

According to formula (1) $v = \frac{2300\nu}{4R} \geqslant 575\frac{\nu}{R}$ cm/sec .

For magnesium alloys with t = 780° $\nu$ = 0.007 cm$^2$/ sec. Then

$$v \geqslant \frac{4.08}{R} \text{ см/сек.} \tag{2}$$

For the calculation of critical ~~velocities~~ velocities at which the metal rises in molds of a specific shape the latter expression can be transformed keeping in mind that R = F/A,

where F is the flow area in cm$^2$;

A is the wetted perimeter in cm.

For example, for a cylindrical cross section with a wall thickness S

$$F = \pi dS, \quad A = 2\pi d.$$

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Then

$$R = \frac{2\pi dS}{2\pi d} = \frac{S}{2}. \tag{3}$$

Substituting (3) into (2) we obtain

$$v < \frac{8.12}{S} \text{ см/сек.} \tag{4}$$

From the above theoretical calculations it ensues that critical velocity is affected only by the thickness of the casting wall. As this increases, the critical velocity at which the metal rises in

molds must decrease.

The above theoretical explanation of the process of filling molds is in good agreement with works on the casting of service parts from alloy ML5. The/critical velocities at which the metal rises in the mold depending on the wall thickness are tabulated in Table 2.

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Table 2

Critical velocities at which the metal rises in molds depending on the thickness of casting walls.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| a) Толщина стенки в *мм* | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| b) Критическая скорость в *мм/сек* | 60 | 40 | 25 | 20 | 15 | 10 | 5 | 3 |

a) wall thickness in mm b) critical velocity in mm/sec.

## The Sequence in Calculating the Number of Sprue Tubes and their Diameters

In order to determine the amount and the cross sections of sprue tubes we first determine the casting time $\tau_{cast}$ proceeding from casting height h and critical velocity $v_{crit}$

$$\tau_{cast} = \frac{h}{v_{crit}} \text{ sec.}$$

Once we know casting time $\tau_{cast}$ and the total weight of the casting p, we determine the overall rate of flow of liquid metal through the all of the sprues;

$$Q = \frac{p}{\tau_{cast}} \text{ g/sec.}$$

The number of sprue tubes n is determined from the design.

Then, the rate of flow of liquid metal during outflow through each tube is

$$q = Q/n \text{ g/sec.}$$

Then, using data from tables and diagrams, the diameter of the sprue of the tube is chosen in accordance with a certain tube height and the calculated rate of flow.

## Basic Advantages of the Directed Successive Crystallization Method

The new casting method makes it possible to obtain workpieces of considerable height with an equal wall thickness (4 mm) which before could not be cast in one piece. As a rule, there is no anisotropy of properties since formation of thin-walled castings takes place at all sections under identical conditions with sufficient feed. Results of the investigation of the mechanical properties of specimens cut in any direction from large size parts cast according to the above method from alloy ML5 are tabulated in Table 3.

Table 3

Mechanical Properties of Specimens Cut From Parts

| | a) Характеристика | b) По ТУ | c) Фактически |
|---|---|---|---|
| d) | Предел прочности при растяжении в $кг/мм^2$ | 16,5 | 18,0—21,5 |
| e) | Предел прочности при сжатии в $кг/мм^2$ | 16,5 | 30,0—39,0 |
| f) | Относительное удлинение в % | 3,0 | 5,0—7,0 |
| g) | Предел текучести при растяжении в $кг/мм^2$ | 9,0 | 10,0—12,5 |
| h) | Предел текучести при сжатии в $кг/мм^2$ | 8.0 | 10,0—13,5 |

a) characteristic b) according to TU c) actually d) ultimate

tensile strength, in kg/mm$^2$ e) ultimate compression strength, in kg/mm$^2$ f) relative elongation, in % g) yield point when stretching, in kg/mm$^2$ h) yield point when compressing, in kg/mm$^2$.

Tests of constructions with cast parts have shown their increased strength as compared with assembled or welded constructions. During static tests failure set in under loads exceeding by 30% and more those established by technical specifications. Switching production to the casting method reduces labor input of mechanical treatment by one-half or two-thirds and increases the utilization factor of the ~~method~~ metal up to 70-75%, i.e., more than fourfold as compared with welded or riveted constructions. Finally, constructions with cast parts are easier ~~xxx~~ to be hermetically sealed than assembled ones.

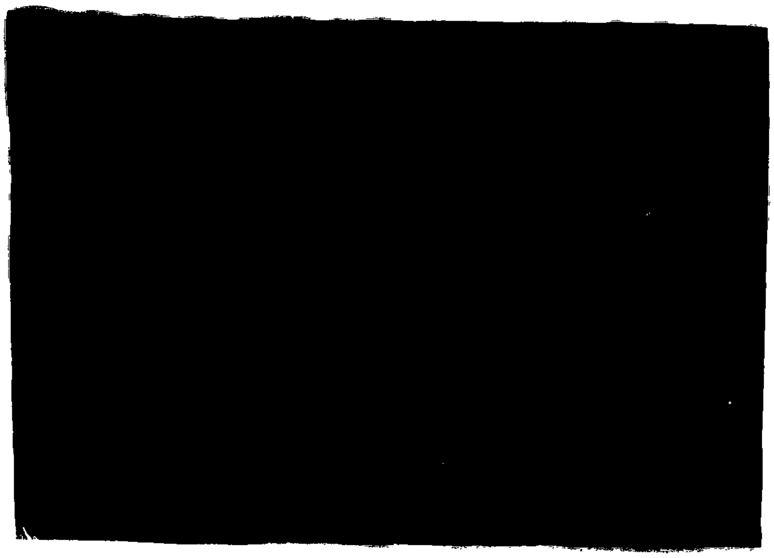

Fig. 11 Beginning of casting.

Ball stoppers preventing the metal from pouring prematurely into the mold are installed on a crosspiece in the pouring basin. The electric wiring for the heating of sprue tubes is visible. The mold is secured to a pull-broaching device beneath the pouring basin. Casting is effected from a special platform by means of a bridge crane.

The following figures show the basic stages of the technological process (Figs. 11, 12, 13) and standard casting machines (Figs. 14, 15).

Fig. 12. Half time of casting. The mold has been slightly lowered. The sprue tubes and the pouring basin are visible.

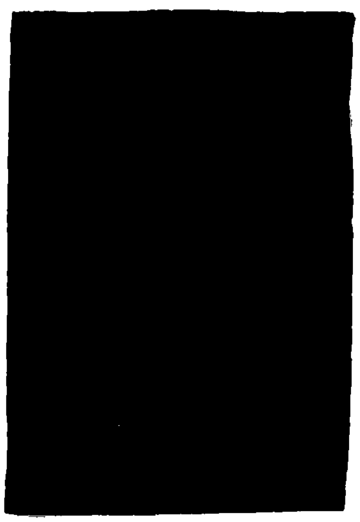

Fig. 13. End of casting. The mold has been lowered into the window of the machine and the sprue tubes have come out from the pits in the mold.

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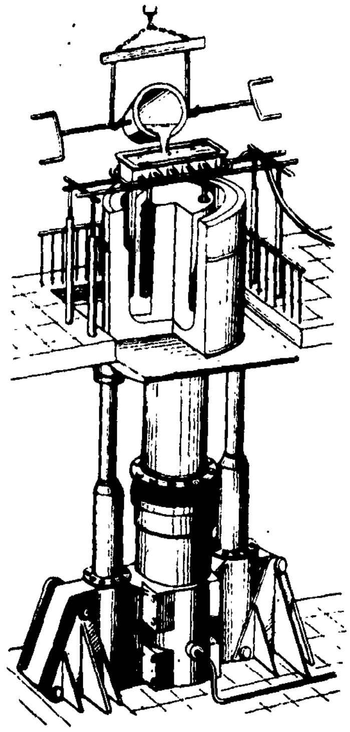

Fig. 14; Casting machine with hydraulic drive .

Fig. 15. Casting machine with mechanical drive.



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PRESSURE CASTING AND ITS HYDRODYNAMIC FOUNDATIONS

V. Ya. Tarutin and Ye. S. Stebakov

Nomenclature

$v_x, v_y, v_z$ - velocity components directed alongthe coordinates x,y,z, in cm/sec;

$p$ - pressure at a given point of the flow in $kg/cm^2$;

$\mu$ - dynamic viscosity factor in dyn x $sec/cm^2$;

$\nu$ - kinematic viscosity factor in $cm^2/sec$;

$\delta$ - casting wall thickness (or cross sectional height of the casting hollow in cm);

$l$ - length of casting, i.e., length in the direction of the flow of metal during pouring into the mold, in cm;

$b$ - casting width, in cm;

$Q$ - liquid metal flow, in $cm^3/sec$;

$v_{mean}$ - mean cross sectional flow velocity, in cm/sec;

$t$ - time in sec;

$v_r$ - velocity component of the fluid flowing on a plane diffusor along the radius-vector $\bar{r}$ which coordinates point M on the plane, in cm/sec;

$v_\varphi$ - velocity component in the diffusor directed along the norm-l towards the radius-vector $\bar{r}$, in cm/sec;

$\alpha$ - angle of dip of the diffusor, in degrees;

$\beta$ - angle of slope of the fixed diffusor wall (or fixed matrix of pressure casting machine) in degrees;

$\varphi$ - angle between radius-vector $\bar{r}$ and the fixed diffusor wall, in degrees;

$g_r$ and $g_{\varphi r}$ - gravity acceleration components directed along radius-vector $\bar{r}$ and a line vertical to it, in cm/sec$^2$;

$\omega$ - angular velocity of the motion of the mobile diffusor wall, in 1/sec;

Re - Reynolds number (dimensionless);

$\rho$ - mass density of any medium, in kg x sec$^2$/m$^4$.

## Some Economical and Theoretical Premises of the Process

Casting is one of the most economical methods for manufacturing parts of the most varied shapes and dimensions. Yet, until very recently there existed no casting methods which would make it possible to cast thin-walled large-size parts.

The difficulty of obtaining thin-walled large-size castings consists in the first place of the fact that it is difficult to fill with molten metal hollows of molds whose cross section looks like narrow slits with great length (1).

In the case of conventional casting the hollow of molds is filled under the pressure of the liquid metal contained in the sprue of the gating system. The potential pressure changes into kinetic energy of metal flow in the channels of the gating system and the hollow of the mold. It is also consumed for overcoming hydraulic resistances arising during motion in these parts of the mold. ~~It~~

(1) In the given case, length is the size of the casting in the direction of the metal flow filling the hollow of the mold.

It has been established in practice (and also proven theoretically) that it is not expedient to increase the height of sprues in gating systems beyond 300-350 mm since this does not increase the flow rate of the metal in the hollow of the mold.

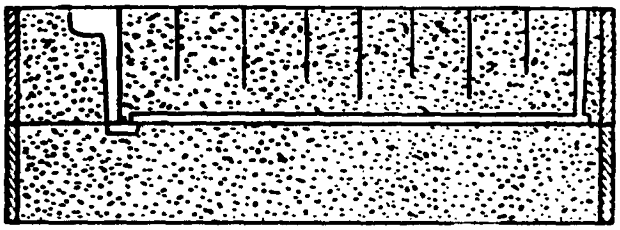

Fig. 1. Cross section of a mold for casting flat thin-walled panels.

When casting into conventional molds, about 30% of the pressure is used for overcoming hydraulic resistances in the channels of the gating system, and about 70% is transformed into velocity head of the liquid metal flowing in the hollow of the mold; resistances in the hollow of the mold are disregarded. Such a simplification is fully admissible since when casting large-size parts their ~~wall~~

wall thickness is never less than 4-5 mm; the metal flow rate in the hollow of them mold is small in this case and hydraulic losses are negligible.

Yet, as the thickness of the casting wall decreases and its length increases, the hydraulic losses rapidly increase and filling the mold with metal becomes more difficult.

In order to find out the degree of intensity with which hydraulic losses increase in the hollow of molds depending on decreases in the thickness of the wall of the cast part in the case of casting thin-walled large-size parts let us investigate by hydrodynamic methods the process of filling molds.

Let us assume that in the sand mold shown in Fig. 1 a flat thin-walled panel is cast according to the usual method (i.e., under hydrostatic pressure from the sprue of the gating system).

After passing through the gating system, the molten metal fills the entire cross section of the hollow of the mold and moves forward in a continuous flow over its entire width. During the filling of the mold the metal flow obeys the laws of motion of viscous fluids flowing horizontally between two parallel walls.

Let us determine the dependence of the magnitude of hydraulic

losses during the flow of molten metal along the hollow of molds on the wall thickness of the casting part. To do this we select a coordinate system in such a way that the x-axis runs in the same direction as the flow and coincides with its axis. The z-axis is perpendicular to the x-axis and the y-axis is perpendicular to the plane xz.

To simplify the problem let us regard the metal flow as isothermal, i.e., that we assume that during the entire time required for filling the mold the metal cools off very slightly and its viscosity remains constant. The metal flow in the cross section investigated is considered plane-parallel and steady. Then the acceleration projections on the coordinate axes equal zero and the velocity components of the y- and z-axes also equal zero.

Let the point M placed at a distance z from the x-axis have the velocity $v_x$ (Fig. 2).

Taking into account the assumptions mentioned above we can write

$$v_x = f(z).$$

We set up a system of differential equations for the motion of the flow under invedtigation and solve it with regard to $v_x$. According to the above assumptions this system takes the following form

$$\frac{\partial p}{\partial x}=\mu\frac{\partial^2 v_x}{\partial z^2}; \tag{1}$$

$$\frac{\partial p}{\partial y}=0; \tag{2}$$

$$\frac{\partial p}{\partial z}=0, \tag{3}$$

where $\frac{\partial p}{\partial x}$ is the pressure gradient along the x-axis;

$\frac{\partial p}{\partial y}$ is the pressure gradient along the y-axis;

$\frac{\partial p}{\partial z}$ is the pressure gradient along the z-axis;

$\mu$ is the dynamic viscosity factor.

The continuity equation takes the form

$$\frac{\partial v_x}{\partial x}=0. \tag{4}$$

It is seen from Equations 1, 2 and 3 that pressure at any point of the flow depends only on the variable x.

We write Equation (1) as

$$\frac{1}{\mu}\frac{\partial p}{\partial x}=\frac{\partial^2 v_x}{\partial z^2}.$$

A 27

After integrating it twice, we obtain

$$v_x=\frac{1}{2\mu}\frac{\partial p}{\partial x}z^2+Az+B, \tag{5}$$

where A and B are the arbitrary constants determined from boundary

conditions.

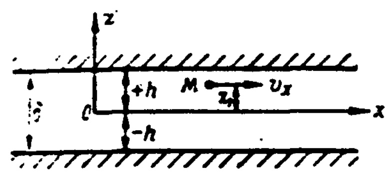


Fig. 2. Coordinates for the solution of the problem relating to hydraulic losses in the hollow of molds.

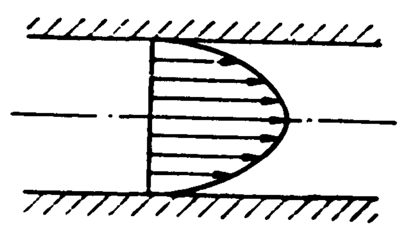

Fig. 3. Parabolic law of the distribution of velocities over the

section of the metal flow.

Since owing to friction the velocity at the mold walls equals zero, the boundary condition according to the diagram shown in Fig. 2 are as follows: 1) with z = +h $v_x = 0$; 2) with z = -h $v_x = 0$.

By substituting these quantities into equation 5 we obtain

B 27

$$B = -\frac{1}{\mu}\frac{\partial p}{\partial x}h^2; \quad A = 0.$$

Hence

$$v_x = -\frac{1}{2\mu}\frac{\partial p}{\partial x}(h^2 - z^2), \qquad (6)$$

where $\frac{\delta p}{\delta x}$ is the pressure differential in the flow for friction.

This formula satisfies the boundary conditions and expresses the parabolic law of the distribution of velocities over the cross section of the flow (Fig. 3).

Once we know the law of the distribution of velocities over the cross section of the flow the pressure differential in the flow can be readily expressed as a function of the liquid flow Q per second and the thickness of the casting wall $\delta$.

From the course of hydraulics we know that

$$Q = b\int_{-h}^{+h} v_x dz, \qquad \text{A 28}$$

where $v_x = f(z)$;

b is the flow width or the dimension of the casting in a direction perpendicular to the drawing plane (see Fig. 2).

If we substitute into this equation the value $v_x$ and integrate, we obtain

B 28

$$Q = -\frac{2b}{3\mu}\frac{\partial p}{\partial x}h^3,$$

whence

$$\frac{\partial p}{\partial x} = \frac{3\mu Q}{2bh^3}. \qquad (7)$$

Taking into account what was mentioned earlier, the pressured differential can be expressed as follows;

C 28

$$-\frac{\partial p}{\partial x} = \frac{p_1 - p_2}{l},$$

where l is the length of the casting.

From a physical point of view this is nothing but hydraulic losses or energy losses of the flow during its motion along the hollow of molds.

In order to determine the rate of growth of these losses with a/continuously ~~constantly~~ decreasing casting wall thickness and its constant dimensions l and b we represent $\frac{\delta p}{\delta x}$ as a function of the casting wall thickness $\delta$ -after having transformed formula 7 beforehand.

From Fig. 2 it is seen that $h = \frac{\delta}{2}$ hence

$$h^2 = \frac{\delta^2}{4}. \qquad \text{D 28}$$

As is known from the course of hydraulics, the liquid flow Q per second equals the product of mean flow velocity $v_{mean}$ multiplied by the flow cross section S:

$$Q = v_{cp} S. \qquad \text{E 28}$$

In the case investigated, i.e., in the case of steady flow, $v_{mean}$ can be expressed by the path length (in our case by the casting length l) and the time of motion of any point on this path (i.e., in our case, the time required for filling the mold)

$$v_{cp} = \frac{l}{t}. \qquad \text{F 28}$$

The cross sectional area of the flow is expressed by the casting width b and the casting wall thickness $\delta$ :

$$S = \delta b. \qquad \text{A 29}$$

Taking this into account, formula 7 can be written as

$$p_1 - p_2 = 12\frac{\mu}{t}\left(\frac{l}{\delta}\right)^2. \qquad (8)$$

In order to represent the rate of growth of hydraulic losses in the hollow of molds with decreasing casting wall thickness it is enough to plot the curve of pressure differentials at the initial

and terminal points of the hollow of the mold as a function of the casting wall thickness:

$$p_1 - p_2 = f(\delta).$$

B 29

In order to plot this curve let us assign any value to the length of the casting in the direction of the flow l and an initial value to the casting wall thickness $\delta_0$.

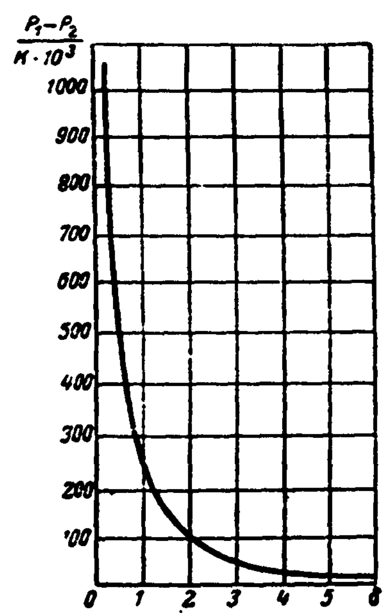


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Fig. 4. Graph $p_1 - p_2 = f(\delta)$.

It is seen from graph $p_1 - p_2 = f(\delta)$ that with a casting wall 6, 5 and 4 mm thick hydraulic losses in the hollow of the mold are negligible and the rate of growth of the losses when passing from 6 to 5 mm and from 5 to 4 mm is infinitesimal. For this reason,

*

Let l = 500 mm and $\delta_0$ = 6 mm. In order to simplify the problem we can assume the multiplier $12\frac{\mu}{t}$ in formula (6) to be a constant quantity equal to a certain value of K.

Function $p_1 - p_2 = f(\delta)$ has the shape of a parabola with one branch asymptotically approaching the ordinate.

in conventional casting where the ratio $1/\delta$ does not exceed 60-80 losses in the hollow of molds as compared to losses in gating systems can be disregarded with an accuracy sufficient for practical purposes.

When casting thin-walled large-size parts where the ratio $1/\delta$ can attain several thousands, the losses in the hollow of the molds increase several hundreds of times and can therefore not be disregarded. In order to overcome the resistances and obtain a timely filling of the hollow of molds, casting of thin-walled large-size parts requires high pressures.

If we bear in mind that the cooling rate of the metal in the mold increases rapidly as the wall thickness decreases owing to which viscosity of the melt strongly increases and its solidification occurs rapidly it becomes evident that molds enabling to cast thin-walled large-size parts cannot be filled by means of conventional casting procedures.

Ways of Solving the Problem of Thin-Walled Large-Size Castings

According to the analysis given above one of the factors rendering difficult the casting of thin-walled panels in conventional molds is the rapid increase of hydraulic losses with decreasing

casting wall thickness and the impossibility of filling the mold before the metal begins to solidify in it. Hence, in order to solve the problem of obtaining thin-walled large-size castings we must find such methods of filling the hollows of molds where hydraulic losses are minimal.

Hydraulic losses in the hollows of molds can be reduced in the following ways.

1. Smoothen the mold walls and reduce counterpressure of the air by pumping it out beforehand from the hollow of the mold.

2. Pour overheated metal into the mold in order to reduce viscosity of the melt, and heat the mold to the melting point in order to prevent the growth of viscosity of the melt and its solidification before the mold has been completely filled.

3. Design machines for pressure casting at pressures required to overcome resistances arising in slit-shaped hollows of molds of assigned dimensions.

4. Design such molds which could be filled by flows with a large cross sections, pour out the metal excesses utilizing thin crusts for the formation of the body which crystallized on the mold walls.

5. Pour metal into the slit-shaped mold from the top only to a depth which can be ensured by the pressure of the sprue of the gating system, then build up the mold by an identical quantity or continuously displace downwards the cyrstallized casting.

The smoothening of mold walls and the creation of a vacuum in the hollow are unable to reduce appreciably the hydraulic losses arising from friction inside the viscous flow between individual streams.

Heating the molds to the temperature of molten metal does increase its capacity of being filled with melt. In this case the metal does not crystallize on the mold walls during pouring and does not increase the resistance on account of increased melt viscosity and decreased through cross section of the mold.

Yet, by heating molds to the melting point we create conditions where successive crystallization in the direction from the mold wall to the center of the casting cannot occur, and the cast part is of low quality owing to the formation of a macrocrystalline structure of the casting body and shrinkage porosity.

Thus, of the five methods of casting metal into molds only three are sufficiently effective: increasing the parameters of

pressure casting machines up to values required for filling molds with great hydraulic losses; partial filling of molds with continuous displacement of the solidified portion of the casting; creation of molds which can be filled with flows with cross sections larger than that of the casting part.

In our country casting of large-size thin-walled parts is being performed according to all of the three methods. Special machines for pressure casting are designed and constructed. (A variety of this method is represented by casting with the aid of controlled low pressures). We also perform casting with top-pouring with continuous lowering of the cast part, i.e., casting according to the successive crystallization method.

We pour metal into opening-up molds which enable [redacted] the filling of their hollows with flows whose cross sections are many times greater than those of the cast parts. This method was proposed in 1951 by Engineer Ye. S. Stebakov who called it "stripping casting".

## Brief Description of "Stripping Casting" and its Hydrodynamic Principles

"Stripping casting" is a basically new technological process.

Casts are formed not as a consequence of solidification of the metal poured into the mold, as in the case of conventional casting, but in a completely different fashion.

It consists of two stages:

1. The stage of formation of casting material in the form of two thin crusts forming on the mold walls during its filling with molten metal.

2. The stage of cast formation by the combination of two thin crusts into one whole - a thin-walled large-size casting.

The mold is constituted by two flaps of the casting-stripping machine. A metal matrix and a sand core are sequred to the flaps.

Prior to the stripping process, molten metal is poured into the bottom part of the mold called metal receptacle. Figure 5 shows the cross section of a mold during stripping.

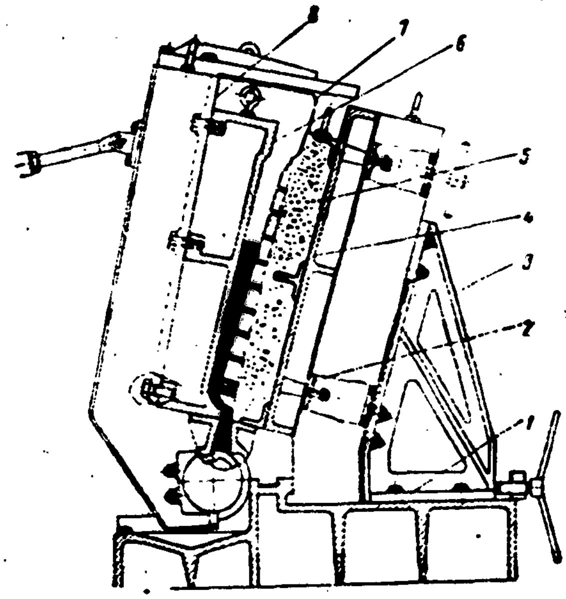


Fig. 5. Cross section of a mold for "stripping casting"; 1. slab 2. fixed flap 3. support 4. intermediate slab 5. sand core 6. material 7. lateral jaw 8. movable flap.

In order to preven the metal from flowing to the side, two side jaws are tightly pressed by springs against the end walls of the mold.

Stripping begins with the displacement of the metallic matrix secured to the movable flap towards the sand core installed on the fixed flap.

While the matrix moves towards the core the metal is pressed out from the metal receptacle and rises in a solid front over the entire width of the matrix filling the hollow of the mold.

During the filling of the mold thin crystallized crusts form on the matrix and the core. When the matrix and the core come closest to one another the excess of liquid metal is expelled from the mold (into a special hollow forming a technological influx) while the crusts combine and form a thin-walled casting whose dimensions are equal to those of the matrix.

The movable matrix is displaced by means of a special device.

Figure 6 shows the cross section of a mold with electro-mechanical drive which displaces the movable flap according to a preassigned law.

Figures 7 and 8 show photographs of a casting and stripping machine VL-1 in its open and closed form.

By displacing the movable flap (matrix) at varying angular velocities we can change the velocity of the metal flow filling the mold.

When displacing the matrix at a constant angular velocity the velocity of metal flow in the mold constantly increases. Figure 9 shows the variation curve of the velocity of metal flow depending on the angle of dip between matrices when they approach one another at a constant angular velocity.

In this case, when the matrix stops there form in the metal form huge inertial forces capable not only of expelling the metal excess from the mold but also to tear the cast which has already formed. Thus, ruptures form in the upper of the cast, or the upper part is torn off completely and expelled from the mold together with the metal excess.

Figures 10 and 11, show photographs of castings with strongly developed (so-called dynamic) cracks and castings with a torn-off upper portion.

Since the angular velocity of the movable matrix can be changed, extrusion casting affords the possibility of totally controlling the filling process of molds.

If we assign the various laws governing the changes in the angular velocity of matrix displacement we can at any moment of the stripping process produce such a velocity of metal flow which would ensure the highest quality of casting.

It ensues from the above that the most important task in developing the theory of extrusion casting consists in determining the dependence between the angular velocity of matrix displacement and the velocity of metal flow in the mold during stripping. This

problem is solved by hydrodynamic methods.

To simplify the problem we replace the hollow of the casting-stripping machine by the hollow of a plane diffusor with a fixed and a movable wall.

Let at the initial moment a portion of viscous liquid be poured into the top of the diffusor which arises when the walls approach one another.

Figure 12 shows a simplified diagram of the process investigated.

We take an arbitrary point M in the flow cross section of the plane diffusor and represent its velocity $v_M$ as a geometrical sum $v_r$ and $v_\varphi$ (1). We determine the velocity components of $v_r$ and $v_\varphi$ as functions of angular velocity $\omega$, the angle of dif $\alpha$, the radius-vector $\bar{r}$, which coordinates the point M in the plane, and the angle $\varphi$ (the angle between the radius vector $\bar{r}$ and the fixed diffusor wall).

(1) $v_r$ - in the direction $\bar{r}$, $v_\varphi$ - along the normal to $\bar{r}$.

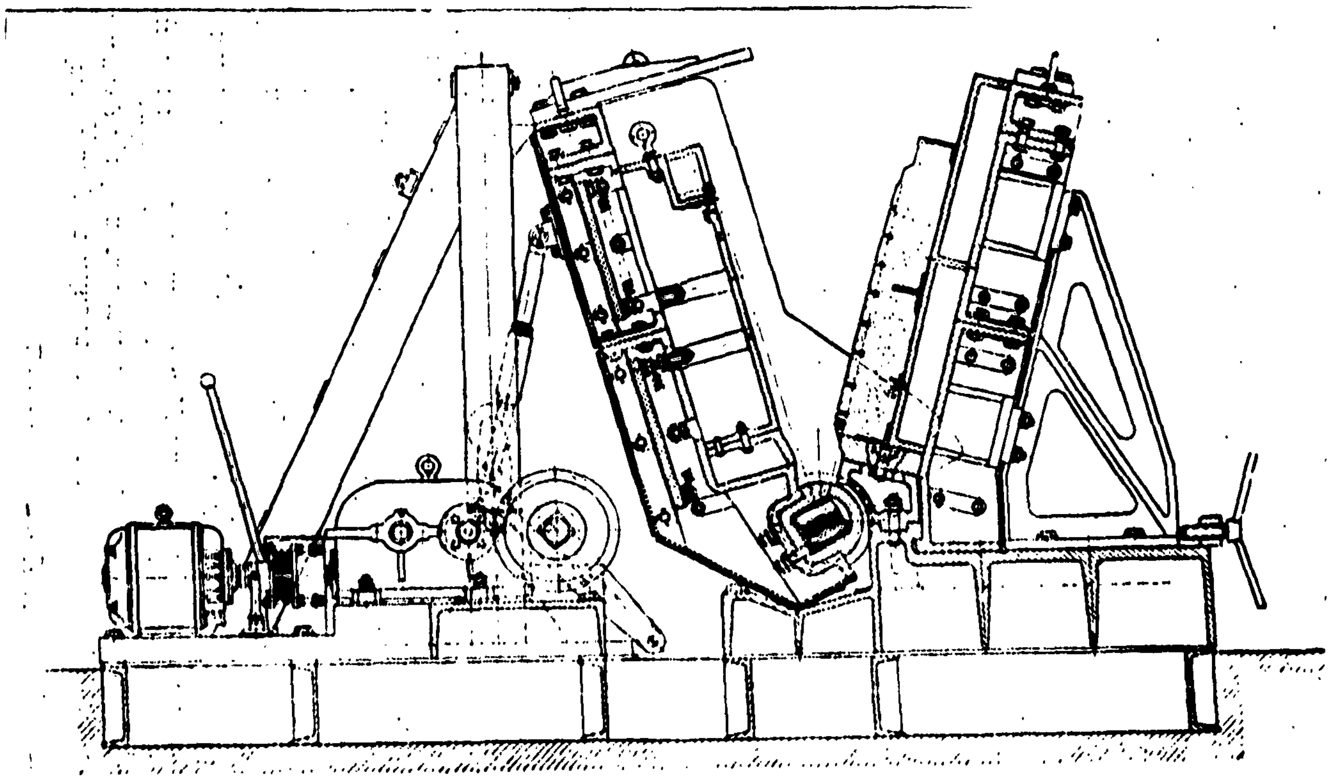

Fig. 6. Cross section of a machine for extrusion casting with electro-mechanical drive.

Fig. 7. General view of a machine for extrusion casting VL-1 (open).

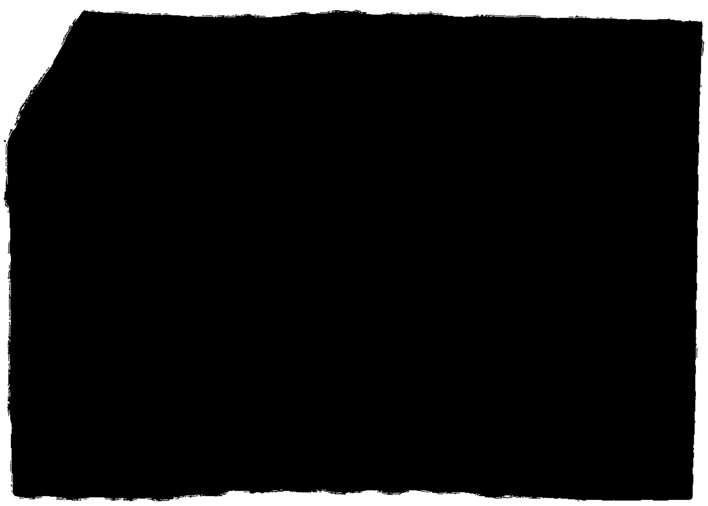

Fig. 8. General view of a machine for extrusion casting VL-1 (closed).



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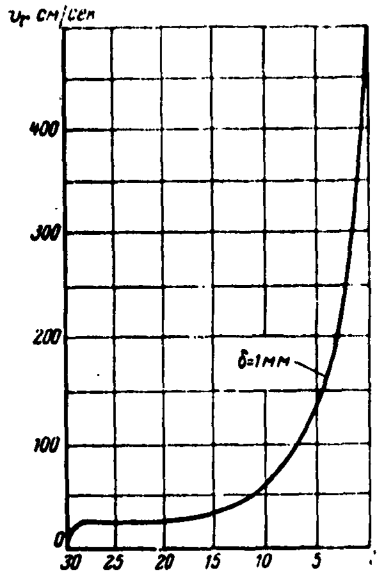


Ψ Angle of dip in degrees

Fig. 9. Curve of the increase in velocity of metal flow in the hollow of the machine for extrusion casting with matrices approaching one another at a constant angular velocity $\omega$.

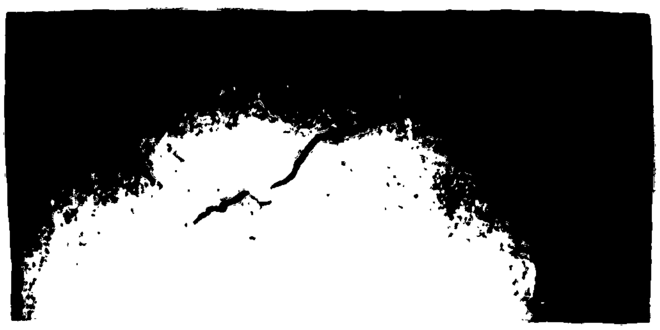

Fig. 10. Dynamic crack in the upper part of casting due to high



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velocity of metal flow at the end of the extruding process.

Fig. 11. Torn-off upper part of casting ~~tx~~ owing to exceedingly high rate of drawing together of matrices.

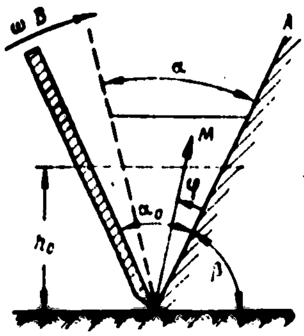


Fig. 12. Cross sectional diagram of a diffusor with analytical solution of the problem relating to velocity fields during extrusion.

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We set up a system of differential equations for the motion of viscous incompressible liquid in a plane diffusor with variable angle of *dip* $\alpha$ and solve it for $v_r$ and $v_\varphi$.

After a number of assumptions which do not change the substance of the phenomenon investigated, and after simplifying the equations of the motion of viscous liquid written in the radial coordinate system we obtain

$$\left.\begin{array}{lr}
\dfrac{\partial v_r}{\partial t}+v_r\dfrac{\partial v_r}{\partial r}+\dfrac{v_\varphi}{r}\dfrac{\partial v_r}{\partial \varphi}-\dfrac{v_\varphi^2}{r}= & \\
=g_r-\dfrac{1}{\rho}\dfrac{\partial p}{\partial r}-\dfrac{2\nu}{r^2}\dfrac{\partial v_\varphi}{\partial \varphi}+\dfrac{\nu}{r^2}\dfrac{\partial^2 v_r}{\partial \varphi^2}-\dfrac{v_r}{r^2}; & \text{(а)} \\
\dfrac{\partial v_\varphi}{\partial t}+v_r\dfrac{\partial v_\varphi}{\partial r}+\dfrac{v_\varphi}{r}\dfrac{\partial v_\varphi}{\partial \varphi}+\dfrac{v_r v_\varphi}{r}= & \\
=g_\varphi-\dfrac{1}{\rho}\dfrac{\partial p}{\partial \varphi}-\dfrac{\nu}{r}\dfrac{\partial v_\varphi}{\partial r}+\dfrac{2\nu}{r^2}\dfrac{\partial v_r}{\partial \varphi}; & \text{(б)} \\
\dfrac{\partial}{\partial r}(r v_r)+\dfrac{\partial v_\varphi}{\partial \varphi}=0. & \text{(в)}
\end{array}\right\} \qquad (9)$$

By solving this system it is possible to express the velocity ~~components~~ components of $v_\varphi$ and $v_r$ as functions of $\alpha$, r, $\varphi$ and $\omega$ :

$$v_\varphi=-\frac{\omega r}{\alpha}\varphi; \qquad (10)$$

$$v_r=\frac{\omega A}{\alpha^2\sin^2\alpha\sqrt{\cos\beta+\sin\beta\,\mathrm{ctg}\,\alpha}}\left(1-\frac{\varphi}{\alpha}\right)\varphi. \qquad (11)$$

where A is a constant factor depending on the angle of inclination

of the fixed diffusor wall $\beta$, on the initial angle of dis

of the diffusor $\alpha_0$ and the initial metal level $r_0$.

The mean cross-sectional flow of velocity equalling $v_{max}/2$, is in this case expressed by formula

$$v_{cp} = \frac{\omega A}{4\alpha \sin^2\alpha \sqrt{\cos\beta + \sin\beta \operatorname{ctg}\alpha}}. \qquad (12)$$

This formula can be considerably simplified. If in the radicand we factor out $\operatorname{ctg}\alpha$ and introduce $\alpha$ ~~in the radicand~~ then we obtain

$$\sqrt{\alpha^2 \operatorname{ctg}\alpha\left(\frac{\cos\beta}{\sin\beta} + \sin\beta\right)} = f_1(\alpha). \qquad \text{A 38}$$

An investigation of the variation of this function with an varying angle from 8° to 0° 10' leads us to conclude that variations in this range can be disregarded ( the metal flows in the mold precisely in this variation range of the angle $\alpha$ ). Then

$$v_{cp} \approx \frac{\omega A'}{\sin^2\alpha}. \qquad (13)$$

By this formula it becomes possible to determine the law of changes in the angular velocity of approaching matrices $\omega$ from any flow conditions of the metal filling the mold during extrusion casting.

Let us, for example, set the condition according to which during the entire time required for the filling of the mold the metal

flow remains laminar. From this condition we determine the law governing the changes in angular velocity $\omega$.

As is known, a flow of viscous fluid remains laminar until the Reynolds numbers do not attain the first critical value. We express the Reynolds number in the flow filling the mold by its geometrical parameters, viscosity and mean flow rate:

$$\mathrm{Re}=\frac{v_{cp} r_{гидр}}{\nu}. \qquad \text{A 39}$$

In our case the hydraulic radius at the end of the process is expressed by the formula

$$r_{гидр}=\frac{b\delta}{2b+2\delta}\approx\frac{\delta}{2}. \qquad \text{B 39}$$

Then the highest value of the Reynolds number during extruding is expressed as follows:

$$\mathrm{Re}_{max}=\frac{v_{cp\,max}}{\nu}\cdot\frac{\delta}{2}. \qquad \text{C 39}$$

By determining $v_{mean}$ by this equality and equating it with $v_{mean}$ from formula (12) and assuming that the Reynolds number remains during extrusion, equalling the first critical value $\mathrm{Re}_{crit\ 1}$ (2320), we obtain

$$\omega=\frac{2\nu \mathrm{Re}_{кр}}{A\delta}\sin^2\alpha. \qquad (14)$$

Hence, if the angular velocity of displacement of the movable

matrix varies during extrusion following the sinusoidal law (proportionally with the square of the sign of the angle of dip between the matrix and the core) then during the entire extrusion process the flow will remain laminar and the filling of the mold will be steady.

We can set up any condition and determine from it the law of changes in angular velocity. Thus, for example, in order that the flow rate during the entire extrusion process remain constant, angular velocity must be changed according to a law expressed by the formula

$$\omega = v_r \frac{2}{\sin\beta} \frac{\sin^2(\alpha+\beta)\sqrt{R^2 + 2F_0 \sin\beta \frac{\sin\alpha}{\sin(\alpha+\beta)}}}{\bar{r}^2}, \tag{15}$$

where $v_r$ is the constant rate of flow of metal in the mold which it is desirable to have during extrusion;

$\beta$ is the angle of slope of the fixed matrix of the machine;

$\alpha$ is the angle of dip of the diffusor (the angle between the matrix and the mold);

$F_0$ is the cross-sectional area of the metal in the receptacle prior to the beginning of extrusion (cross section of the diffusor and a vertical plane);

R

$\bar{r}$ is the height at which the metal rises with a given angle of dip of the diffusor determined by the formula

$$\bar{r} = \frac{2F_0}{\delta + \sqrt{\delta^2 + 2F_0 \sin\beta \frac{\sin\alpha}{\sin(\alpha+\beta)}}}; \qquad A \quad 40$$

$\delta$ is the wall thickness of the panel being cast.

Figure 13 shows the graph of the variation of angular velocity ensuring laminar metal flow during extrusion, while Fig. 14 shows the graph of velocities which can be obtained with the aid of the device shown in Fig. 6.

When casting panels 2200 x 80 mm in size with a wall thickness of 2.5-3 mm , extrusion lasts for 6-8 sec. Towards the end of the extrusion process the flow rate attains 0.8 m/sec. Consequently, crystallization crusts form on the matrix and the core under conditions of steady flow of the fluid phase of the melt.The flow of the fluid phase exerts a considerable effect on the conditions and character of crystallization.

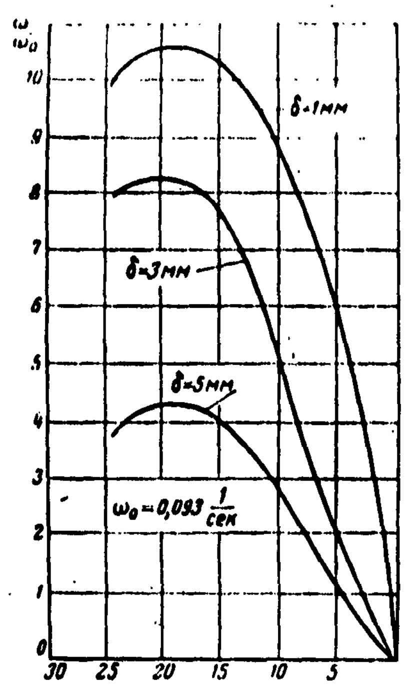
The continuous flow from the metal receptacle of metal hotter than at any other point of the mold maintains a high temperature gradient in the boundary layer during the entire~~x~~ process of crust formation.

Figure 15 shows the diagram of a temperature field in the metal

cross section cooling off on the mold walls under steady conditions and under conditions of the fluid melt phase continously flowing between mold walls.

The high temperature gradient in the boundary layer promotes crystallization in the thin layer and the formation of a fine-grained structure of the casting body. Moreover, the flow washes off a part of the intermediate melt phase thus slowing down the crystallization process and contributing to the formation of crusts with great density.

Casting by extrusion creates exceptionally favorable conditions for the intensive feeding of crystallizing layers with liquid melt. During the entire crystallization process the crystallizing layers touch the liquid metal. The continuous compression of the flow when the matrices approach one another as well as the continuous rising of the metal level in the mold increase pressure and press the liquid metal into the intercrystalline cavities.




Angle of dip in degrees

**Fig.** 13. Graph of the variation of angular velocity of approaching matrices ensuring laminar metal flow during extrusion.


Angle of dip in degrees

Fig. 14. Graph of velocities of approaching matrices which can be obtained with the aid of the electromechanical drive shown in Fig. 6.

Figure 16 shows how the liquid metal feeds the layers crystallizing on the mold walls.

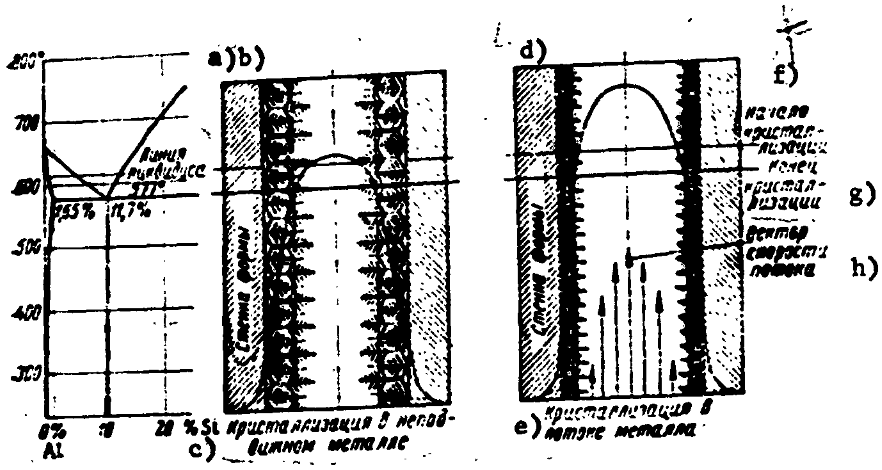



Fig. 15. Diagram of temperature fields during cooling of metal in molds in the case of motionless and flowing metal. a) liquidus line b) mold wall c) crystallization in motionless metal d) mold wall e) crystallization in flowing metal f) beginning of crystallization g)end of crystallization h) flow rate vector.

Continuous flow of liquid metal near the crusts crystallizing on the mold walls creates favorable conditions for degassing of the melt in the boundary layer.

Gas bubbles (as well as light non-metallic inclusions) contained in the flow are washed by streams of varying velocities and the gas mass inside the gas bubble is bound to acquire a rotating motion. Figure 17 shows the diagram of a gas bubble washed by a flow of liquid metal.

We can see that here the potential flow overlaps with the eddy.

As is known from hydrodynamics, in this case the pressures on the eddy surface are distributed in such a way as to promote the displacement of the eddy under the effect of these pressures towards higher velocities of the incident flow.

Figure 18 shows the flow lines and the distribution of pressures on the surface of the eddy washed by a flow of viscous liquid.

Proceeding from the diagram shown in Fig. 17 we can set up a system of equations for the eddy and the overlapping potential flow and, by solving it, determine the paths of gas bubbles in the metal

flow during extrusion.

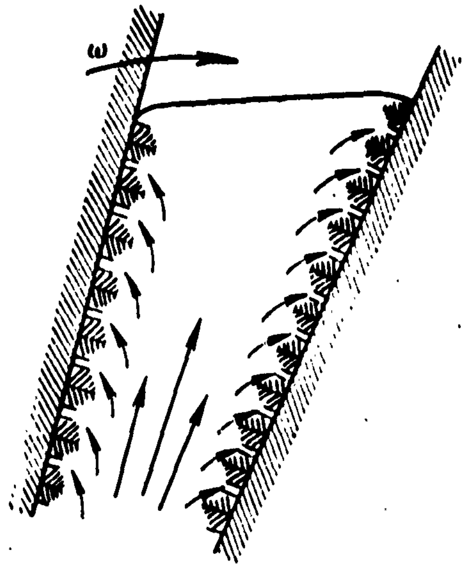



Fig. 16. Diagram of crystallizing layers fed by liquid melt phase.

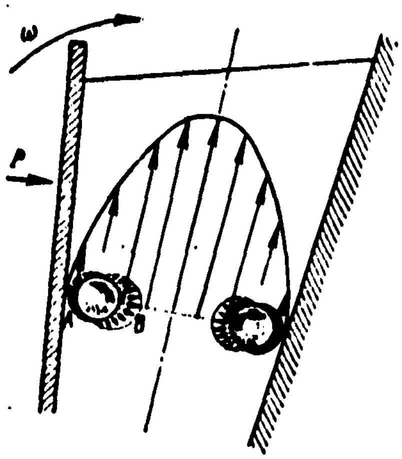



Fig. 17. Flow diagram of a gas bubble in a flow of liquid metal.

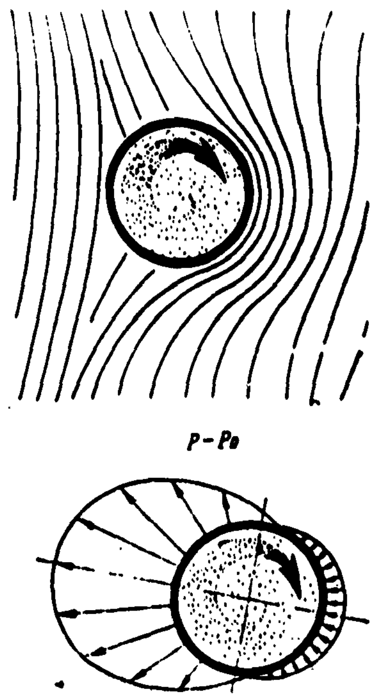



Fig. 18. Gas eddy in a metal flow: flow lines (top) and distribution of pressures on the surface of an eddy washed by a potential flow (bottom).

Assuming that the intensity of gas rotation inside the gas bubble reamins constant, proportional to a certain mean value of linear flow rate, these systems can be written as follows

$$\left.\begin{aligned} m\frac{dv_x}{dt} &= -2\rho\omega S v_y - A\rho S v_y \\ m\frac{dv_y}{dt} &= -2\rho\omega S v_x - B\rho S v_x, \end{aligned}\right\} \tag{16}$$

where m is the gas mass inside the bubble;

$v_x$ and $v_y$ are the velocity components of the bubble motion;

A and B are resistance forces of the medium;

T is the time;

$\rho$ is the mass density of the gas inside the bubble;

$\omega$ is the angular velocity of gas rotation inside the bubble.

By solving this system it becomes possible to express the path of the gas bubble as a function of time. This solution has the form

$$\left.\begin{aligned} x &= x_0 + 2\omega y t \\ y &= \frac{\delta}{2}\sin\pi\left(1 - \frac{t}{2}\right), \end{aligned}\right\} \tag{17}$$

where $x_0$ is the coordinate x at the initial instant of time;

$\omega$ is the angular velocity of gas rotation inside the bubble;

$\delta$ is the mold wall thickness;

y is the distance from the wall varying from 0 to $\delta/2$ ;

t is the time.

Figure 19 shows two paths of a gas bubble. One of them was drawn analytically according to formulas (17), while the other was plotted on the basis of tests conducted with a transparent model of a machine for extrusion casting with various viscous liquids.

It ensues that when casting by extrusion the hydrodynamic action of the metal flow in the hollow of a mold affects substantially the formation of the casting body. If obtained by means of extrusion, this body consists of two thin and solid crusts which formed on the mold walls during the filling process.

By changing the hydrodynamic conditions of the filling process of the mold with metal, we can control the formation of the casting body.

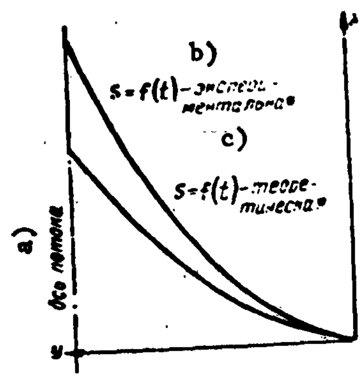



Fig. 19. Paths of a gas bubble drawn analytically and on the basis of test data. a) flow axis b) experimental c) theoretical.

Thus, besides controlling the heat removal from the metal to the mold, the engineer can also control the velocity of metal flow during the filling of molds.

CONCLUSIONS

The study of casting by extrusion has shown the economic expediency of a large-scaled application of this new technological process.

The hydrodynamic characteristics of casting by extrusion con-

tribute to removing gases and solid inclusions from the melt as a result of which the casting walls are strong and plastic.


Fig.208 Two photographs of a smooth thin-walled panel cast by extrusion and rolled in a sold state into a roll (two projections).

Figure 20 (a,b) shows two photographs of a thin-walled panel rolled in a cold state into a roll. Such a roll can be straightened and there will be no tears or cracks.

The high purity of the surface and the high accuracy of the geometrical dimensions of panels cast by extrusion makes it possible to convey the cast panels to the assembly line without any mechanical processing of their profiles. Some deburring on a milling machine of the contact plane of panels represents a very small portion of the overall labor input required by the workpiece.

A considerable advantage of the new technological process consists in the possibility of casting panels of huge sizes with a wall thickness of 2-3 mm with any position of ribs, various beaded edges and bosses, as well as casting hollow thin-walled parts.

Cast thin-walled panels can be widely used in many branches of national economy. Thus, for example, it is possible to cast the panels of hoods of motor cars and trucks, hulls and overhead covers of small ships, railway tank cars, many parts of agricultural

machines, parts of tanks for everyday usage,etc.

Thin-walled panels cast with secondary alloys can be widely used in the construction industry as facing materials and, in some cases, as parts of some structures.

Casting by extrusion is a very new technological process. Much of it has not been studied as yet. At the present time MATI chairs undertake extensive researches in order to determine the thermal, hydrodynamic and technological conditions of this casting method.

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